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TRACING THE GALACTIC THICK DISK TO SOLAR METALLICITIES[1]

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ABSTRACT

We show that the Galactic thick disk reaches at least solar metallicities, and that it experienced strong chemical enrichment during a period of ~ 3 Gyr, ending around 8-9 Gyr ago. This finding puts further constraints on the relation and interface between the thin and thick disks, and their formation processes. Our results are based on a detailed elemental abundance analysis of 261 kinematically selected F and G dwarf stars in the solar neighborhood: 194 likely members of the thick disk and 67 likely members of the thin disk, in the range $-1.3 \lesssim$ [Fe/H] $\lesssim +0.4$.

Subject headings: Galaxy: disk — Galaxy: formation — Galaxy: evolution — solar neighbourhood — stars: abundances — stars: kinematics

1. INTRODUCTION

The Milky Way has since the early 1980s been known to have two disk components, a thin disk and a thick disk (Gilmore & Reid 1983). Since then, several studies, using high-resolution spectra to derive elemental abundances in disk dwarf stars, have been aimed at establishing the properties of the thick disk, and to better understand its origin and role in our Galaxy (e.g., Gratton et al. 2000; Prochaska et al. 2000; Fuhrmann 2004; Mishenina et al. 2004; Reddy et al. 2006; Bensby et al. 2003, 2005). The thick disk is now known to be a major Galactic stellar population, and that its stars have hotter kinematics, higher ages, and are chemically distinct from the stars of the thin disk. All this points to separate origins and different chemical histories for the thin and thick disks.

Recently, a lot of structure has been observed amongst the stars in the Galaxy. In the disk in the solar neighbourhood this is seen as various stellar streams and moving groups (e.g. Famaey & et al. 2005; Helmi & et al. 2006); and at larger distances, features such as e.g. "The Field of streams" (e.g. Belokurov et al. 2006) have been detected. So, did the thick disk form as a single entity in the initial collapse of the protogalactic cloud (e.g., Eggen et al. 1962), and/or is it a result of an ancient merger event, or is it made up of a stars coming from streams and merger debris, i.e. a hierarchical origin (e.g. Abadi et al. 2003; Brook et al. 2004; Robertson et al. 2004)? A persistent question is why the Milky Way has two disk populations.

Abundance trends and the metallicity distribution function of the thick disk are vital records to its formation and evolution. However, the high metallicity limit of the thick disk remains poorly defined. For instance, Fuhrmann (2004); Mishenina et al. (2004); Reddy et al. (2006) suggest that the thick disk extends only up to [Fe/H] ≈ -0.3, because their candidate thick disk stars at higher [Fe/H] either fall within their thin disk abundance trends and/or have highly eccentric orbits that are near the Galactic plane. Hence their origins should be sought elsewhere, perhaps in stellar streams like the Hercules stream (see e.g. Famaey & et al. 2005). But, even if possible Hercules stream stars are weeded out, stars with thick-disk-like kinematics at high [Fe/H] still remain (Soubiran & Girard 2005; Bensby et al. 2007, see also Fig. 1). Furthermore, in Bensby et al. (2003, 2004, 2005); Bensby & Feltzing (2006) we find that the thick disk stars differ significantly from the thin disk stars, both in terms of abundance ratios as well as stellar ages, even at [Fe/H] close to solar. However, those results are based on a small stellar sample and need confirmation.

As described, the current data for the metal-rich thick disk are confusing and ambiguous. It is therefore necessary to isolate the thick disk abundance relations from those of other populations. Therefore, we have carried out an extensive spectroscopic survey of metal-rich stars that are kinematically associated with the Galactic thick disk. In this Letter, we discuss Ti and Ba abundance trends, and combine our new results with our thin and thick disk results from Bensby et al. (2003, 2005). Other α-, r-, s-, and iron peak elements will be discussed in an upcoming paper (Bensby et al., in prep) together with the details of the kinematic selection criteria and the abundance analysis.

2. SELECTION OF TARGETS, OBSERVATIONS AND ABUNDANCE ANALYSIS

The kinematic method from Bensby et al. (2003, 2005) was used to select possible thick disk F and G dwarf stars from the Nordström & et al. (2004) catalogue. Briefly, the method assumes Gaussian velocity distributions for all stellar populations, and that the solar neighbourhood can be represented as a mixture of only the thin disk, the thick disk, the Hercules stream, and the halo. Candidate thick disk stars are selected as those that have probabilities of belonging to the thick disk that are at least twice the probabilities of belonging to any of the other populations (and likewise for the other populations). The space velocities for the 159 new thick disk and 10 new thin disk stars are shown in Fig. 1a-c together with 35 thick disk and 57 thin disk stars from Bensby et al. (2003, 2005). Also shown, in Fig. 1d-e, is how the thick disk-to-thin disk probability ratios (TD/D) vary with [Fe/H].

Echelle spectra were obtained in 2005 and 2006 with the MIKE spectrograph, on the Magellan Clay 6.5 m

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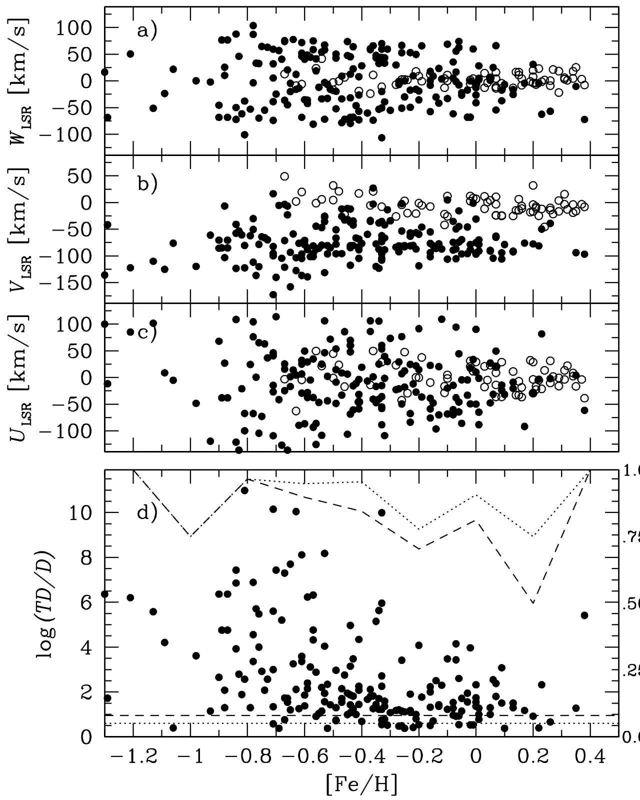

FIG. 1.— *(a)-(c):* Velocity-metallicity plots for the stellar sample. Thin disk and candidate thick disk stars are marked by open and filled circles, respectively. *(d):* TD/D probability ratios versus metallicity for the thick disk candidates. Bottom lines indicate $TD/D = 4$ (dotted line) and $TD/D = 9$ (dashed line). Lines on top give the corresponding fraction of stars that have TD/D larger than these ratios (scale on the right hand side). [Fe/H] values are from our spectroscopic work.

telescope, for 145 new thick disk stars ($R \approx 65\,000$, $S/N \gtrsim 250$), and in 2004 with the UVES spectrograph, on the ESO Very Large Telescope, for 14 new thick disk and 10 new thin disk stars ($R \approx 110\,000$, $S/N \gtrsim 250$).

The MARCS model stellar atmospheres (Gustafsson et al. 1975; Edvardsson & et al. 1993; Asplund et al. 1997) were used in the abundance analysis. Excitation balance, and balance with line strength, of abundances from Fe I lines, were used to determine effective temperatures and the microturbulence parameter. For the surface gravities we exploited accurate distances based on *Hipparcos* parallaxes (ESA 1997). Final abundances were normalised on a line-by-line basis with our solar values as reference and then averaged for each element.

Stellar ages were determined with the help of the Yonsei-Yale (Y^2) isochrones (Kim et al. 2002; Demarque et al. 2004), with appropriate α-enhancements, in the $T_{\rm eff}$-$M_{\rm V}$ plane. Upper and lower limits on the ages were estimated from the error bars due to an uncertainty of ± 70 K in $T_{\rm eff}$ and the uncertainty in $M_{\rm V}$ due to the error in the parallax (see also Bensby et al. 2003).

3. RESULTS AND DISCUSSION

3.1. *Abundance trends*

Figure 2 shows the resulting [Ti/Fe] and [Ba/Fe] versus [Fe/H] trends. The stars associated with the thick disk first show a [Ti/Fe] plateau at [Fe/H] $\lesssim -0.4$, a signature of fast enrichment from massive stars. At higher metallicities, the thick disk [Ti/Fe] ratio declines, indicating the delayed enrichment from SN Ia. The thin disk shows an overall shallow decline in [Ti/Fe], characteristic of slow enrichment by *both* massive and low-mass stars. At [Fe/H] ≈ 0, the trends for the two disks converge.

[Ba/Fe] for the thick disk evolves almost in lockstep with [Fe/H]. As solar metallicity is approached, the thin and thick disk [Ba/Fe] trends diverge. At [Fe/H] > 0 it again becomes hard to differentiate the two disks.

Both [Ti/Fe] and [Ba/Fe] versus [Fe/H] demonstrate that kinematically hot stars associated with the thick disk extend to solar metallicities. However, it is also evident that there are thick disk stars that do not follow the general thick disk abundance trends. Instead, they chemically behave as thin disk stars. This is at least evident in the [Ti/Fe]-[Fe/H] plot as [Fe/H] ≈ 0 is approached.

To try to determine the nature of these ambiguous stars, we use the thin disk sample (Figs. 2b and e) to visually define boundaries on [Ti/Fe] and [Ba/Fe] for the thin disk (shown as solid lines in the *upper four panels* of Fig. 2). The number of candidate thick disk stars that fall within the thin disk abundance trends are shown in the *bottom two panels* of Fig. 2. There is a steady increase with metallicity of candidate thick disk stars that fall within the thin disk [Ti/Fe] trend, suggesting that the contamination from the high-velocity tail of the thin disk increases with [Fe/H]. The fraction that fall within the thin disk [Ba/Fe]-[Fe/H] trend is, on the other hand, generally small, and with no apparent trend. This suggests that essentially all candidate thick disk stars could be genuine thick disk stars.

Due to the closeness of the thin and thick disk [Ti/Fe] trends at higher [Fe/H] one can expect true members of the thick disk to fall within the thin disk trend, and vice versa. And, since the Ba abundances are based on only 3-4 Ba II lines, there are larger measurement uncertainties in [Ba/Fe] than in [Ti/Fe]. Ba abundances could also be influenced by NLTE effects, hyperfine and isotopic structure, and blends from other spectral lines (see, e.g., Mashonkina & Zhao 2006); effects that we have not accounted for. On the other hand, we present a strictly differential abundance analysis. If the above effects were severe, we would not find well-defined and distinct Ba trends for two kinematically selected samples. Hence, we believe that our Ba abundances are well determined.

3.2. *Age trends*

The top panel in Fig. 3 shows the age distributions for the candidate thick disk stars that follow the thick disk [Ti/Fe] trend (as defined by the thin disk boundary line in Fig. 2a) while the middle panel shows those that do not. Each sub-sample has been divided into four metallicity bins, as shown. The bottom panel shows the age distributions for the thin disk sample.

The candidate thick disk stars with thin disk [Ti/Fe] ratios appear to be younger than those above the boundary. For instance, in the $-0.35 <$ [Fe/H] < 0 bin, only one out of 26 candidate thick disk stars (4 %) that have a thin disk [Ti/Fe] ratio is older than 8 Gyr. In the same metallicity bin, 23 out of 33 stars (70 %) that re-

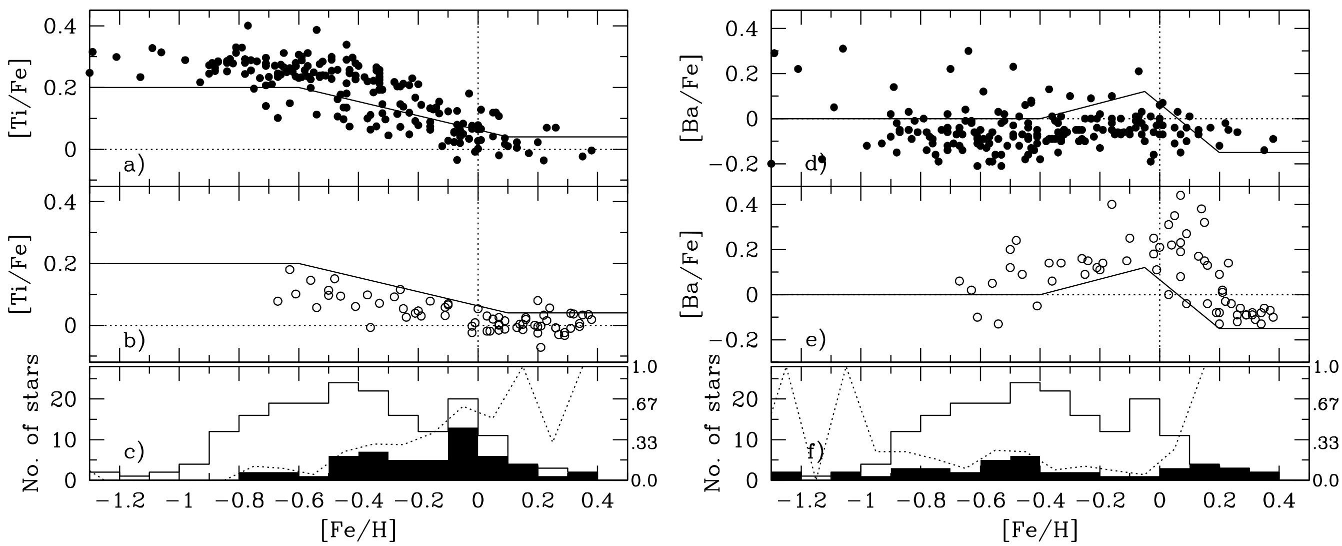

FIG. 2.— *Top four panels:* [Ti/Fe] and [Ba/Fe] versus [Fe/H]. Thin and thick disk stars are marked by open and filled circles, respectively. Solid lines marks the boundary for the thin sample. *Bottom panels:* Distribution of all 195 thick disk stars *(white histograms)*, and the thick disk stars that fall within the thin disk abundance trends *(black histograms)*. The dotted line in the bottom panels shows the fraction (scale on the right-hand side) of thick disk stars in each bin that fall within the thin disk abundance trends.

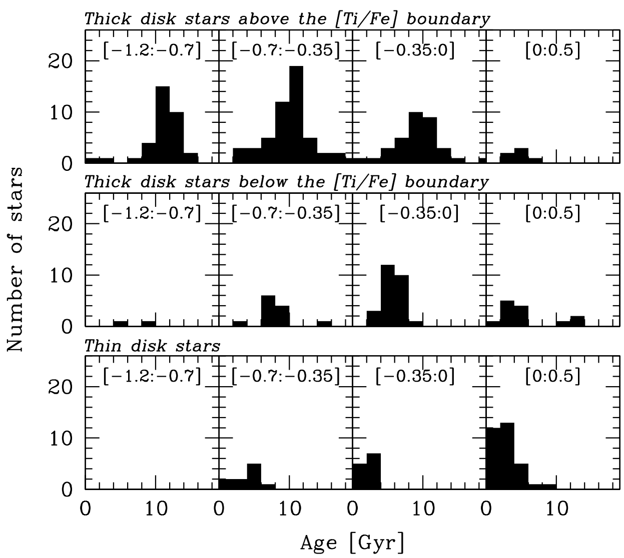

FIG. 3.— Top and middle panel show age distributions for thick disk stars that fall above and below the [Ti/Fe] boundary, respectively. Bottom panel shows the thin disk distribution. All age distributions are divided into four metallicity bins, as indicated in the square brackets at the top of each panel.

main above the thin disk [Ti/Fe] boundary are older than 8 Gyr. This duality in both ages and abundances again points to two distinct Galactic disk populations, both reaching [Fe/H] = 0.

Figure 4 shows [Fe/H] and [Ba/Fe] as a function of age, excluding stars with estimated upper and lower age limits (see Sect. 2) that differ by more than 35 %. Running medians of the ages for the thick disk, calculated in steps of 0.1 dex in [Fe/H], using a 0.2 dex wide window in [Fe/H], both with and without thick disk stars that have thin disk [Ti/Fe] ratios, are shown in Fig. 4a. For [Fe/H] $\lesssim -0.8$, median ages are typically ~ 12 Gyr. The median age at higher [Fe/H] depends on whether thick disk candidates that have thin disk [Ti/Fe] ratios are included or not. As many of the stars that fall below the

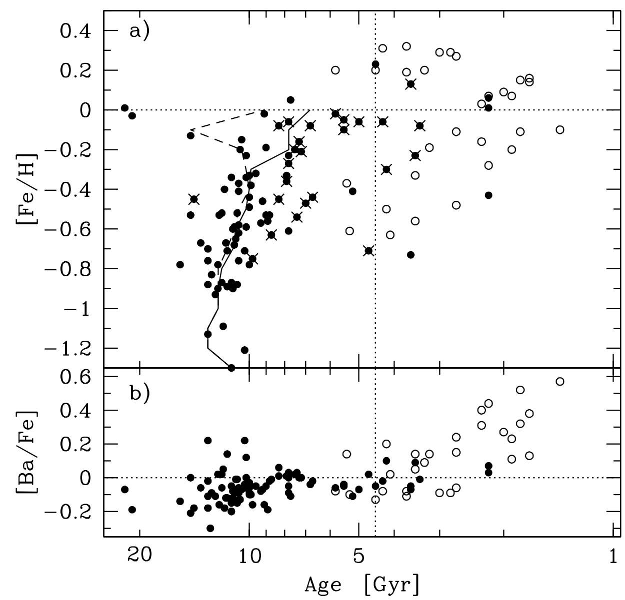

FIG. 4.— [Fe/H] and [Ba/Fe] versus age. Stars for which the upper and lower age estimates differ by at most 35 % are included. Thin and thick disk stars are marked by open and filled circles, respectively. The solid line shows the running median ages (see text) for the thick disk stars, and the dashed line when excluding thick disk stars that have thin disk [Ti/Fe] values (marked by crosses). The vertical, dotted line, is the age of the Sun (4.5 Gyr).

[Ti/Fe] boundary have ages comparable to the stars that do not, it is likely that the actual relation is intermediate to the solid and dashed lines. The age of the thick disk at solar metallicities is then ~ 9 Gyr, i.e. it takes the thick disk ~ 3 Gyr to reach [Fe/H] ≈ 0.

3.3. *The metal-rich end of the Galactic thick disk*

Our kinematically hot stars appear to come from an old stellar population, with ages of 8-12 Gyr, that extend at least to [Fe/H] ≈ 0. This population is not only old, but also its stars have kinematic properties typical of

the Galactic thick disk, and chemical properties similar to what is found in the Galactic thick disk. Furthermore, preliminary results show that the abundance and age trends do not vary with either of the $U_{\rm LSR}$, $V_{\rm LSR}$, and $W_{\rm LSR}$ velocities (Bensby et al. in prep., but see also Bensby et al. 2006). Therefore, this appears to be manifest evidence that this stellar population indeed is the Galactic thick disk. That the thick disk really reach all the way up solar metallicities verifies the existence of the "knee" present in most thick disk [α/Fe] trends. Hence the thick disk formed stars for at least 3 Gyr and experienced strong enrichment, from both SN II and SN Ia, during this period, ending $\sim$ 8-9 Gyr ago.

3.4. *The relation between the thin and thick disks*

In our sample, the most metal-poor stars with thin disk kinematics have metallicities of [Fe/H] ≈ -0.7 and ages around 5 Gyr. Hence, these stars are considerably younger than the most metal-rich thick disk stars at [Fe/H] ≈ 0 whose ages are 8-9 Gyr. At super-solar metallicities, the thin disk stars appear to have ages comparable to those of the most metal-poor ones, i.e. ~ 5 Gyr, suggesting that they formed at the same time! This phenomenon could be explained by the infall of gas into the Galaxy, which initially was poorly mixed with the remains of the old metal-rich gas. The first stars of the thin disk could then be metal-rich ($\gtrsim 0.3$), metal-poor ($\lesssim -0.5$), or, depending on the degree of mixing of the gas, of any metallicity in the range $-0.7 \lesssim$ [Fe/H] $\lesssim +0.4$. This scenario may explain why there is no well-defined age-metallicity relation in the solar neighbourhood (e.g., Edvardsson & et al. 1993; Feltzing et al. 2001; Haywood 2006). However, we caution that age uncertainties can be large and that the increase in dispersion of the metallicity with stellar age, for nearby stars, partly could be due to migration of stellar orbits (e.g., Haywood 2006; Wielen et al. 1996).

Figure 4b shows [Ba/Fe] versus stellar age. The two disks appear to follow smoothly in time and there also appears to be a quiescent period of 1-2 Gyr when almost no stars were formed, some 6-7 Gyr ago. However, our thin disk stellar sample has by no means been selected to probe its oldest parts. Hence, a possible hiatus, and the fact that that there are (a few) stars that have ages in betwen the two disks, should be investigated with a sample targeted for the oldest thin disk.

Figure 4b also helps to further understand the origin and evolution of Ba in the Galactic disks. The "bump" in the thin disk [Ba/Fe]-[Fe/H] trend (Fig. 2e) is no longer seen. As the most metal-rich thin disk stars evidently are not the youngest ones there is now instead a steady increase in [Ba/Fe] toward younger ages. The first, flat portion of the [Ba/Fe] trend is consistent with being due to the r-process. As the s-process becomes significant (due to AGB stars), [Ba/Fe] will rise. The position of the Sun is consistent with an origin during the early times of the thin disk, when Ba enrichment was mainly r-process dominated but started to give way to being s-process dominated. However, we caution that the solar Ba composition is thought to be $\sim 80\,\%$ s-process and $\sim 20\,\%$ r-process (e.g., Arlandini & et al. 1999).

4. SUMMARY

We have presented clear evidence that the Galactic thick disk reaches at least solar metallicities, and thus that it experienced strong chemical enrichment during an early period ending some 8-9 Gyr ago.

The plot of [Ba/Fe] versus time, instead of [Fe/H], offers a more straightforward interpretation of the evolution of Ba at high metallicities.

We find that even the most metal-rich stars of the thick disk are older than the thin disk population, with a possible hiatus in the star formation between these two populations. We are continuing to investigate these relationships with a stellar sample designed to target the oldest stars of the thin disk.

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